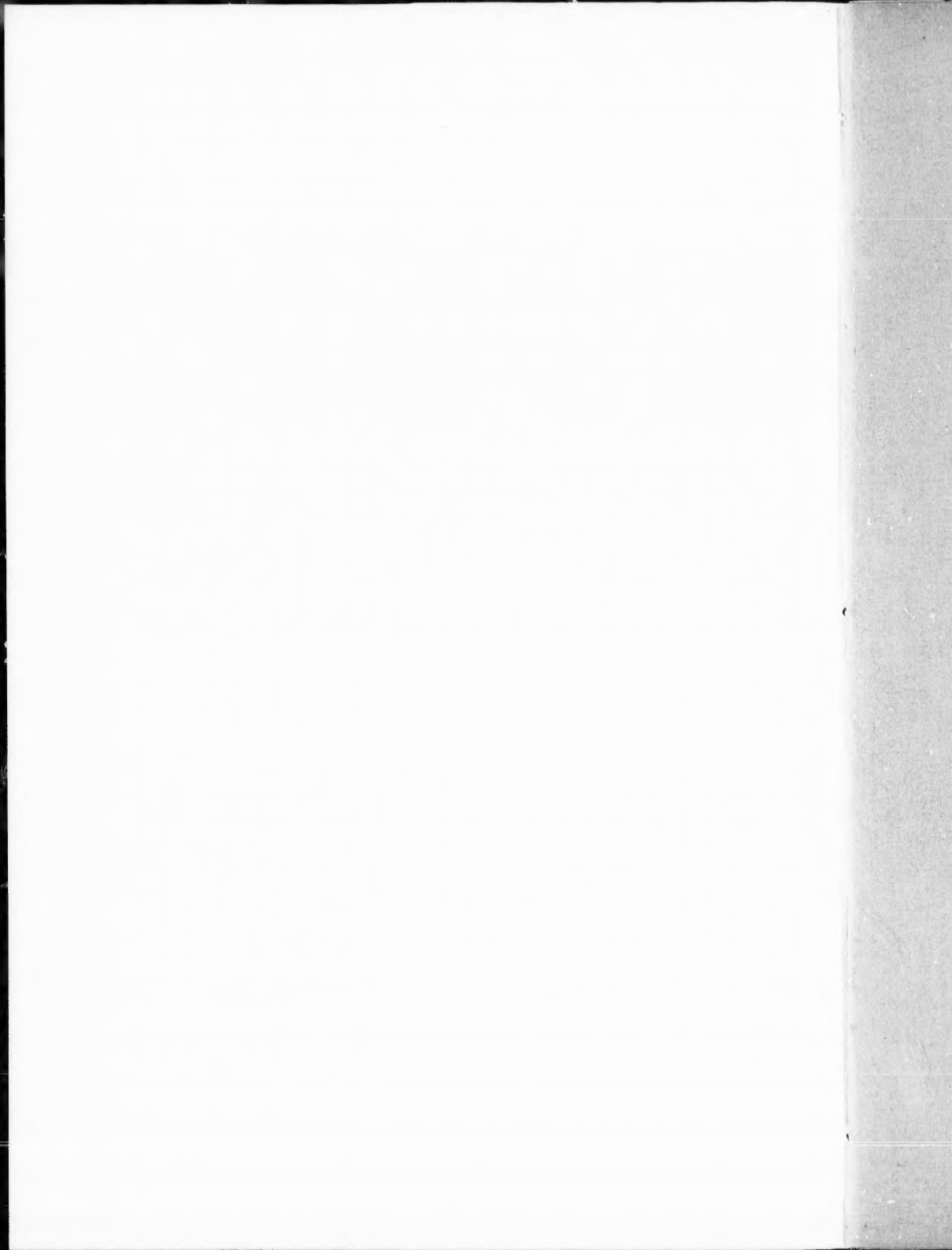




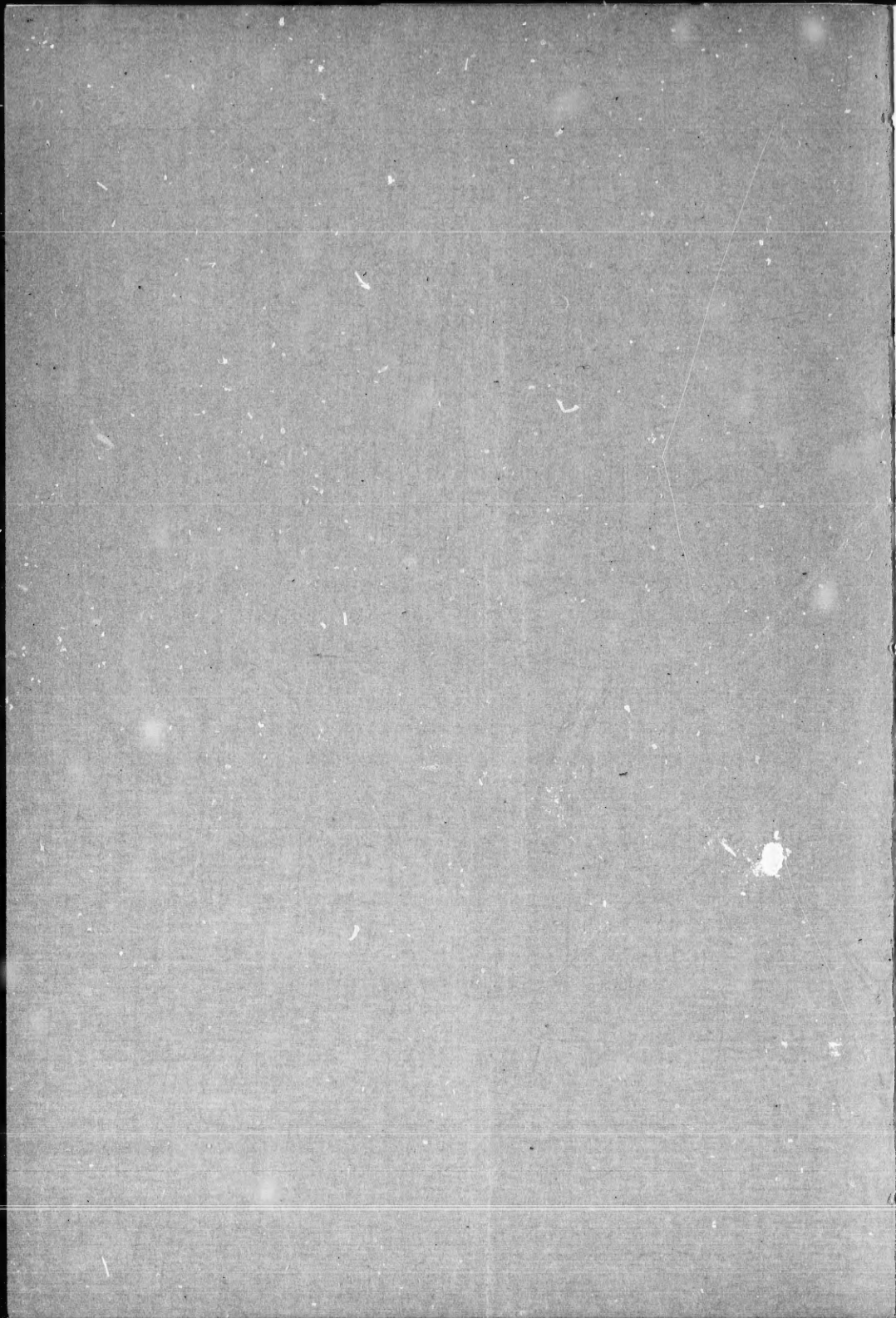
CRYSTALS.

BY

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CRYSTALS.*

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of Canada.

I have nothing original to offer you on this subject, nor are my remarks intended to constitute a lecture on crystallography, but merely to bring to your notice some interesting facts with regard to those wonderful forms which we call crystals, and more especially to trace out the progress made in the study of them since the earliest times. The subject is so vast that it will only be possible for me to call attention to some of the more prominent and interesting facts, which constitute, as it were, the milestones along the road of our knowledge of the subject.

At the outset we are confronted with the question "What is a crystal?"

So many definitions have been given that it is somewhat difficult to select one which is expressed in simple terms and at the same time is comprehensive and accurate.

E. S. Dana says:—"Structure in Inorganic nature is a result of mathematical symmetry in the action of cohesive attraction. The forms produced are regular solids called *crystals*; whence morphology is, in the Inorganic kingdom, called CRYSTALLOLOGY. It is the science of structure in this kingdom of nature."

He subdivides the subject as follows:—

Crystallogeny	Crystallography	{ treating of forms resulting from crystallization.
	Crystallogeny	{ treating of the methods of making crystals, and the theories of their origin.

* (Read before the Ottawa Field Naturalists' Club, Dec. 20th. 1894.)

Naumann's definition of a crystal is a very concise and satisfactory one. It is this :—"Any rigid inorganic body possessing an essential and original (primitive) more or less regular polyhedric (many-sided) form *which is directly connected with its physical properties.*"

This latter clause of the definition is very important as explaining why cleavage fragments, pseudomorphs &c. are not to be termed crystals.

To the question *why* calcite, for instance, should assume one form of crystal, and garnet another, science can return no answer, but must content itself with determining and describing these curious and multifarious forms.

The word "crystal" is derived from the Greek word "*κρυσταλλος*" meaning "ice". The ancients first gave this name to the variety of quartz which we call "Rock-crystal," because, from its transparency, its usual freedom from color, and the way in which it was found to enclose other bodies, they imagined it had been formed by the action of intense cold on water, which thus became extraordinarily hardened.

The name was later transferred to pure transparent stones, such as were after used for seals and engraved gems.

Some of the old writings on this subject are very amusing. Albertus Magnus, in the middle of the 13th century, gravely relates how the intense cold on the summits of some lofty mountains *dries* the ice so thoroughly that it becomes crystal. Even as late as 1672 the learned Robert Boyle goes into a long dissertation to prove that crystal could not be ice, adducing as two of the strongest proofs of this, first, the fact that ice floats on water and crystal does not, and, secondly, that Madagascar, India, and other countries in the torrid zone, abound in crystal, and he could not believe that any ice, however hard, could withstand the heat of those countries. Later the term "crystal" was applied to any mineral naturally limited by plane faces.

It was not until 1669 that any important discovery regarding the properties of crystals was made, and then it was that Nicolaus Steno, a Danish physician, discovered for the first time the constancy of angles in Rock-crystal. But it is generally admitted that Steno himself did not fully grasp the importance of his dis-

covery, which was more a deduction from the mathematical form of the particular body he observed than a broad generalization from a series of observations of different bodies. It must be borne in mind that the ancients knew and had described crystals of certain minerals as having a *constant number* of faces (or planes) arranged in a *particular way*. But Steno went further than this and shewed that another constant existed. He cut a number of sections of variously shaped prisms of quartz (1.) at right angles to the edges of the prism, and (2.) at right angles to the edge formed by a face of a pyramid with a face of the prism and found in the first case (see Fig. 1) that the angles of any one section were equal to each

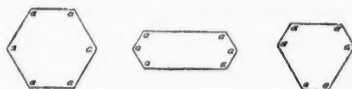


Fig. 1.

other and also to every angle of the other similar sections, and in the second case (see Fig. 2) he found that the sections had two angles equal



Fig 2.

to b and four angles equal to c , except when the prism was absent in the crystal, when the section was a four-sided figure with two opposite angles equal to b , as shewn on the left in Fig. 2.

His inference was that in all specimens of Rock-crystal corresponding pairs of faces have the same inclination.

Thus was taken the first step towards the discovery of one of the three great fundamental laws governing the formation of crystals, which has been enunciated thus:—

THE LAW OF CONSTANCY OF ANGLES. Crystals of the same substance, whether natural or formed in the laboratory, are essentially constant in the angle of inclination between like planes.

For a whole century the law discovered by Steno was not elaborated until,

in the year 1772, Romé Delisle, a pupil of Linnæus, shewed that the various shapes possessed by crystals of the same substance, natural or artificial, are all intimately related to each other. He formed a large collection of natural crystals which he carefully studied and was particularly interested by the fact that the same mineral often occurred in widely different forms. His studies led him to the conclusion that the shape of every crystal of the same substance is such as can be derived by a particular process from a certain fundamental figure called the *Primitive Form*, the shape and angles of which depend only on the nature of the substance itself. All the multitudinous forms which a substance such as pyrite (sulphide of iron) assumes, he found could be produced by replacing the edges or the solid angles of the primitive form by single planes or groups of planes, but always in such a manner that the total alteration is similarly related to all parts of the primitive form which are geometrically similar.

Thus, as a simple example, by cutting off the angles of a cube it may be converted into an octahedron. These planes of replacement were regarded by him as being secondary and more or less accidental.

Werner in his treatise "On the External Characters of Minerals" had employed the terms *Abstumpfung* = truncation, *Zuscharfung* = beveling, *Zuspitzung* = acumination, in speaking of similar variations or changes from the fundamental form of crystal, but it is thought that Delisle did not know of this at the time he wrote. Delisle set to work to determine the primitive forms of all substances, which work was greatly facilitated by the invention at this time of the goniometer. This instrument was invented by a Frenchman named Carangeau, who prepared the clay-models used by Delisle to illustrate his theory. It was designed for the measurement of solid angles, particularly those of crystals, and was of the form known as the common or *contact goniometer*.

A much more elaborate and accurate instrument for the same purpose is the *reflecting goniometer* of Dr. Wollaston, devised by him in 1809, of which several elaborate modifications are now employed by crystallographers. Carangeau's goniometer consisted essentially of a graduated arc and two moveable arms. Its form may be learned by referring to the figures given in almost all text-books of mineralogy. The great

objection to it is that it is impossible to employ it in the case of very small crystals, whilst the reflecting goniometer may be used to measure accurately the angles of crystals only $\frac{1}{100}$ th of an inch in size.

Romé Delisle, as the result of his researches, came to the conclusion that the primitive forms of all known substances were only six in number, namely :—

1. The cube.
2. The regular octahedron.
3. The regular tetrahedron.
4. The rhombohedron.
5. The octahedron with a rhombic base.
6. The double six-sided pyramid.

These were announced in his treatise on Crystallography published in 1783, in which he figures no less than 500 distinct forms of crystals.

The weak point of his theory was the fact that the whole series of forms of any one substance could be derived not only from the *primitive form*, but from almost any of the series, thus rendering it impossible to lay down an exact rule as to which of these was to be regarded as the true primitive form. He was guided in his choice by the largeness of development and frequency of occurrence of particular faces and the simplicity of the figure they formed. Thus he chose both cube and regular octahedron, although, as we now know, these forms really belong to one and the same series and may be derived the one from the other. Many of his contemporaries doubted not only his choice of primitive forms but the very existence of the series, and Buffon's objections, as set forth in his "Natural History of Minerals" published ten years later (1783), bore testimony to the difficulty of the important step taken by Romé Delisle. It was far from being obvious that all the crystalline forms of a mineral belong to one series.

As early as 1773, Bergman, a celebrated Swedish chemist, shewed in his writings that he recognized the importance of cleavage, and by it he tried to explain the relationship of the various forms assumed by the same mineral, which had so interested and puzzled Delisle, who, however, assigned little or no importance to cleavage, speaking, as he does in the preface to his treatise mentioned above, most contempt-

uously of the "*brise-cristaux*" or "crystalloclastes." But Bergman did not proceed far enough, and it remained for another to fully develop the theory of the structure of crystals as indicated by their cleavage.

In 1784 the Abbé Haüy made his remarkable discovery, which, like Newton's immortal one, was the result of a mere accident.

A six-sided prism of calcite (carbonate of lime) had been broken from a large group in the cabinet of M. Defrance, and he noticed that the fractures were smooth and polished, not irregular as in the case of broken glass. He then commenced splitting-up the crystal with his knife and finally reduced the six-sided prism to a rhombohedron. Extending his experiment to other minerals Haüy arrived at the conclusion that the kernel obtained from a mineral by cleavage was to be regarded as its true primitive form.

E. S. Dana defines *cleavage* as the tendency to break or cleave along certain planes due to regularity of internal structure and fracture, produced, in addition to external symmetry of form, by crystallization; and he states two principles:—

(1) In any species, the direction in which cleavage takes place is always parallel to some plane which either actually occurs in the crystals or *may* exist there in accordance with certain general laws.

(2) Cleavage is uniform as to ease parallel to all like planes. That is to say that if it may be obtained parallel to *one* of the faces of a regular octahedron, for instance, it may be obtained with the same facility parallel to each of the remaining octahedral faces.

Haüy's primitive forms were ten in number, four more than those of Romé de l'Isle. They were:—

1. The cube.
2. The regular octahedron.
3. The regular tetrahedron.
4. The rhombic dodecahedron.
5. The rhombohedron, obtuse or acute.
6. The octahedron, with square, rectangular, or rhombic base.
7. The four-sided prism, with edges at right angles to the base, the base being either a square, a rectangle, a rhomb, or merely a parallelogram.

8. The four-sided prism, with edges inclined obliquely to the base, the base being either a rectangle, a rhomb, or merely a parallelogram.
9. The regular six-sided prism,
10. The double six-sided pyramid.

He also grouped all these forms in a general way thus:—

1. Figures bounded by parallelograms.
2. Figures bounded by eight triangles.
3. The regular tetrahedron.
4. The regular six-sided prism.
5. The double six-sided pyramid.

Haüy was led by his study of cleavage to frame a theory regarding the *structure* of crystals and to discover a second great law governing their formation, namely the one which connects the secondary faces with those of the primitive form.

He found that the kernels which he obtained by cleavage could be split-up, apparently indefinitely, into smaller fragments of the same shape, and, not believing that this process could go on to infinity, came to the conclusion that every crystal of the same substance could, theoretically at least, be cleaved into minute bricks of a definite size and shape though too small to be separately visible, and therefore that with these bricks a crystal possessing any of the forms in which the particular mineral occurs, might be built up.

As the simplest illustration take the case where the bricks are little cubes. The conditions to be produced are that the built-up crystal must possess cleavage, and at all its parts the faces obtainable by cleavage are to have the same directions, also that its outer surface must consist of a series of plane faces.

A cube composed of these little bricks could be increased indefinitely in size by adding layers of these bricks to each of its faces. Conversely, it might be decreased in size by taking away the layers.

But suppose that the decrease takes place by the regular subtraction of one or several ranges of bricks in each successive layer; theory, by calculating the number of these ranges required for a particular form, can represent all known forms of crystals and also indicate *possible* forms for a particular mineral which may not yet have been observed in the

natural crystals. Figs. 3 and 4 will serve to illustrate what we have just been discussing.

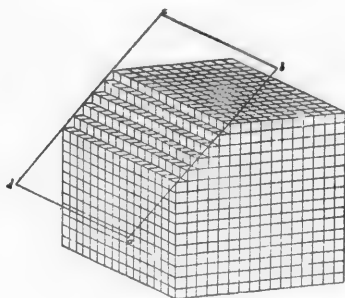


Fig. 3.

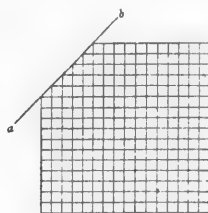


Fig. 4.

Fig. 3 illustrates a cube composed of little cubical bricks, some rows of which are removed to shew the resulting step-like arrangement of the layers. All the edges of the steps lie in one plane, as seen in Fig. 4.

If we remember that the little bricks are supposed to be so minute as to be separately invisible, it will be seen that the steps will appear to lie wholly in the plane, which thus forms a secondary face equally inclined to two faces of the cube.

Haüy also shewed how a rhombic dodecahedron resulted from the application of successive layers of these little bricks, each less by one row all round, to the faces of the primitive cube, and of course the same result may be obtained by subtracting rows in the same manner. (See Fig 4.)

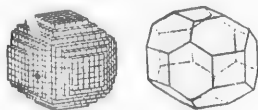
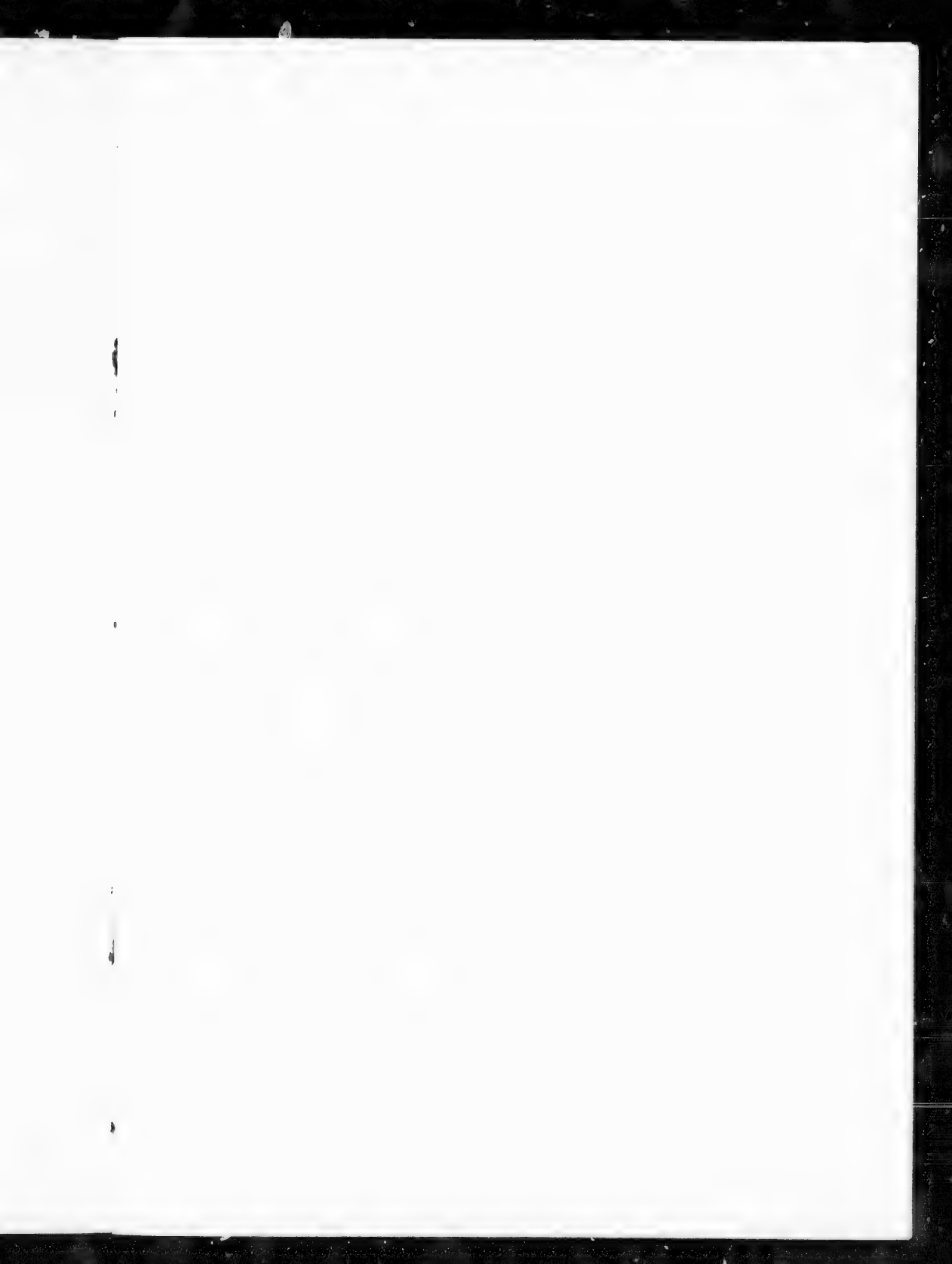


Fig. 5.

He also assumed in some cases that the decrease was parallel, not to the edges of the crystal, but to a diagonal, taking the angles as its point of departure. His theory established the fact that the various





forms of crystals are not irregular or accidental, but definite, and based on certain fixed laws; and he pointed out that whilst certain forms are derivable from a given nucleus, there are others which cannot occur.

Moreover he observed that when any change in a crystal took place by its combination with other forms, all similar parts (angles, edges and faces) were modified in the same way. Most important of all, he shewed that these changes could be indicated by *rational* co-efficients.

Thus Haüy became the discoverer of two of the three great laws of crystallography, namely, THE LAW OF SYMMETRY, and THE LAW OF WHOLE NUMBERS. The other, THE LAW OF CONSTANCY OF ANGLES, we have already mentioned.

Let us consider for a moment Haüy's two laws, taking first :—

THE LAW OF SYMMETRY.

E. S. Dana enunciates this as follows: "The symmetry of crystals is based upon the law that either :

- I. *All parts of a crystal similar in position with reference to the axes are similar in planes or modification, or*
- II. *Each half of the similar parts of a crystal, alternate or symmetrical in position or relation to the other half, may be alone similar in its planes or modifications.*

The forms resulting according to the first method are termed *holohedral* forms and those according to the second, *hemihedral*."

An easy experimental way of studying the symmetry of crystals is to cut one, or the model of one, in two, and place the parts against the surface of a mirror, which may or may not produce the *exact* appearance, of the original crystal. If it does produce the *exact* appearance we have severed the crystal in a *plane of symmetry*. By referring to Fig. 6 it will readily be seen that a cube, for instance, possesses *nine* such planes, indicated by the dotted lines.

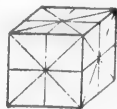


Fig. 6.

In a sphere there would of course be an infinite number of these planes.

Now with regard to the second law :—

THE LAW OF WHOLE NUMBERS. The meaning of this is simply that Haüy found that the secondary faces had only such positions as would result from the omission of *whole* numbers of rows of bricks and from the layers having a thickness measured by some multiple of that of a single brick. He actually proved by measurements that the number of bricks in the width or height of a step rarely exceeds six. But Haüy's theory of the structure of crystals had many weak points in it which speedily became objects of attack. One of his first critics was Weiss, Professor of Mineralogy at Berlin, who translated Haüy's work into German, in 1804.

He shewed that Haüy's "primitive forms," as professor Nichol puts it, "erred both in excess and defect," and that the "bricks" were not needed at all to explain the facts observed, in fact, the planes, so-called, built up of them, would not reflect light.

Bernhardi, a doctor residing in Erfurt, pointed out that the dimensions of the "primitive forms" could not be determined from themselves, their height depending on another form. Also that various crystals, which he named, were much more readily explained from other forms than those taken by Haüy as their "primitives". In fact, numberless objections were raised; thus, it by no means follows that because a crystal may be reduced to a certain form by cleavage, that its growth has resulted from the grouping together of fragments having that form; again, some minerals have no cleavage, whilst others cleave only in one or two directions; again, it is hard to conceive of a crystal built up, for instance, of little octahedrons, which, in order to have their faces parallel to the cleavages of the resulting crystal, and be parallel to each other, would have only their angular points in contact, thus forming a most skeleton-like and unstable structure.

But Haüy's theory, pointing as it did to the great importance of the angles of the faces and cleavages of crystals, served to direct attention to them, and led to their more accurate study and determination.

It was not so much Haüy's data that required correction, but the substitution of a better theory to connect his facts was needed.

The development of the atomic theory of the constitution of

matter furnished this, and, instead of "bricks", we reason about "atomic groups," whose centres of mass are arranged in straight lines and parallel planes, as were the centres of the "bricks" in Haüy's original theory.

Weiss was the first, in 1808, to point out the importance of the axes of crystals, although Haüy had referred to them.

He says :—"The axis is truly the line governing every figure round which the whole is uniformly disposed. All the parts look to it, and by it they are bound together as by a common chain and mutual contact." These axes, it must be borne in mind, are not mere geometrical lines; but it is in reference to them that the forces work which have formed the crystals.

Weiss proceeded to arrange Haüy's *primitive* forms into four classes, each distinguished by a purely geometrical character; and then from these four classes of sets of lines, he deduced all the *primitive* forms by the construction of planes passing :—

1. Through ends of three lines.
2. Through ends of two of the lines and parallel to the third.
3. Through an end of one of the lines and parallel to two of them

That is, these planes passed through the end of a line, or else did not meet it at all. These axes were, in fact, the co-ordinates of the crystal faces of the *primitive* forms of Haüy. By taking points along each of these lines at distances equal to twice, three times, four times, etc., the original length, he found, constructing planes as before, that he obtained a set including all the *secondary* planes described by Haüy as occurring in actual crystals.

Thus he was enabled to devise a very simple system of designating the various faces of crystals, which also greatly facilitated the calculation of their angles.

Haüy had attempted this in conformity with his theory, but his symbols were complex and unwieldy.

It is a curious coincidence that at the same time as Weiss was developing his system, Mohs, Werner's successor at Freiberg, working quite independently, arrived at the same division of crystals into four classes, but by a very different process of reasoning. These four classes he termed "Systems of Crystallization."

Mohs also shewed that since all the similar edges and solid angles of his fundamental figures were to be similarly altered, the existence of one derived plane necessitated, as in Romé Delisle's theory, the simultaneous existence of a number of others having definite positions. Such a set of faces he called a *simple form*. If the faces of more than one simple form are present, the resulting form was termed a *combination*.

At this time Sir David Brewster was engaged in his wonderful researches on the optical properties of crystals, and the results of his experiments on the polarization of light brought out in such a remarkable manner the intimate relations existing between their behaviour with regard to light passing through them, and the number of kinds of axes they possessed, that Whewell has justly said, "Sir D. Brewster's optical experiments must have led to a classification of crystals into the above systems, or something nearly equivalent, even if the crystals had not been so arranged by attention to their forms."

Sometimes crystals were observed by both Weiss and Mohs which, instead of being complete simple forms, like the regular octahedron, presented only *half* the regular number of faces, as, for example, the regular tetrahedron, which may be derived from the regular octahedron by suppressing its alternate faces. Delisle and Haüy had regarded the tetrahedron as a distinct kind of primitive form, but Weiss and Mohs found it necessary to postulate that simple forms may not only be complete, but semi-complete also, pointing out, however, that the half which presents itself is not an arbitrary one, but can always be derived systematically from the complete simple form.

The complete simple forms were termed *holohedral*, and the semi-complete ones *hemihedral*.

In 1822, Mohs added two more systems of crystallization to the four already described by Weiss and himself; but Weiss brought forward very strong objections to their recognition, and their independence was not fully established until 1833, when the actions on light of crystals belonging to these systems were first studied. They were what we now call the *monoclinic* and *triclinic* systems.

The researches of Weiss and Mohs may be said to have given to

crystallography its present form, in all essential points, as a pure science, and subsequent progress has been along the lines of working out details rather than modifying its foundations.

The accompanying table, (page 130), will shew at a glance the six systems of crystallization now recognized, with their principal synonyms and examples of minerals for each system.

Very often crystals are met with in which one or more parts are reversed with regard to the others, often presenting the appearance of two crystals symmetrically united. These are termed *twin crystals*, but the theory of their formation is too elaborate to be gone into in the present paper. Time will not permit me, either, to go into details respecting the various methods of designating the faces of crystals by numbers or symbols, and of calculating their angles. That of Naumann is, perhaps, the one most employed. This subject belongs, however, more to pure geometric crystallography, and will be found fully explained in the text-books. I can only briefly mention here some of the many wonderful physical properties possessed by crystals.

The researches of Brewster on polarized light have already been referred to. The discovery that the shape of the cleavage-form is intimately related to the action of the crystal upon light is due to him; and his researches, as already mentioned, confirmed the existence of the two additional systems of crystallization recognized somewhat doubtfully by Mohs.

One of the most remarkable discoveries of recent times was the mathematical demonstration by von Lang, Quenstedt, and others, that six, and *only* six, systems of symmetry are possible for all crystallized matter.

In 1822, Mitscherlich announced his discovery of *isomorphism*, the property which substances analogous in chemical composition possess of crystallizing in forms closely resembling each other, and with only a slight difference between their corresponding angles. A good example is siderite and dolomite, the crystal form being a rhombohedron. Mitscherlich also pointed out that the same substance (simple or compound) may crystallize in two distinct systems (*dimorphism*), or even in three or more (*trimorphism* and *polymorphism*). Thus the sulphide of iron crystallizes in the isometric system (*pyrite*), and also in the orthorhombic system (*marcasite*).

SYSTEMS OF CRYSTALLIZATION.

NAME.	AXES.	PLANES OF SYMMETRY.	EXAMPLES.
I. ISOMETRIC. — <i>Tessular</i> , Mohs & Haidinger. <i>Isometric</i> , Hausmann. <i>Tesseral</i> , Naumann. <i>Regular</i> , Weiss & Rose. <i>Cubic</i> , Dufrenoy & Miller. <i>Monometric</i> , Dana (early editions.)	Three, of equal length, intersecting each other at right angles.	Nine.	Fluor Spar. Galena. Pyrite.
II. TETRAGONAL. — <i>Pyramidal</i> , Mohs. <i>Zwei-und-einaxige</i> , Weiss. <i>Tetragonal</i> , Naumann. <i>Monodimetric</i> , Hausmann. <i>Quadratic</i> , von Kobell. <i>Dimetric</i> , Dana (early editions)	Three, intersecting each other at right angles. The lateral ones equal in length; the vertical a varying one	Five.	Zircon. Vesuvianite. Cassiterite.
III. HEXAGONAL. <i>Rhombohedral</i> , Mohs. <i>Drei-und-einaxige</i> , Weiss. <i>Hexagonal</i> , Naumann. <i>Monotrimetric</i> , Hausmann. NOTE.—This System has a RHOMBOHEDRAL DIVISION, which includes forms with only 3 planes of symmetry.	Four, the three equal lateral ones intersecting at angles of 60° and the vertical one, at right angles to these, varying in length.	HEX. proper. Seven; 3 at 60°; one normal to these; three auxiliary. RHOM. DIV Three at 120°.	Calcite. Quartz. Apatite.
IV. ORTHORHOMBIC. — <i>Prismatic</i> or <i>Orthotype</i> , Mohs. <i>Ein-und-einaxige</i> , Weiss. <i>Rhombic</i> and <i>Anisometric</i> , Naumann. <i>Trimetric</i> and <i>Orthorhombic</i> , Hausmann. <i>Trimetric</i> , Dana, (early editions.)	Three, of unequal length, intersecting each other at right angles.	Three, at right angles to each other.	Barite. Topaz. Aragonite.
V. MONOCLINIC. — <i>Hemiprismatic</i> and <i>Hemiorthotype</i> , Mohs. <i>Zwei-und-eingliedrige</i> , Weiss. <i>Monoclinohedral</i> , Naumann. <i>Clinorhombic</i> , von Kobell, Hausmann, Des Cloiszeaux. <i>Augitic</i> , Haidinger. <i>Oblique</i> , Miller. <i>Monosymmetric</i> , Groth.	Three, of unequal length, two intersecting at right angles and the third intersecting one of the others obliquely.	One.	Augite. Gypsum. Orthoclase.
VI. TRICLINIC. — <i>Tetartoprismatic</i> , Mohs. <i>Ein-und-eingliedrige</i> , Weiss. <i>Triclinohedral</i> , Naumann. <i>Clinorhomboidal</i> , von Kobell. <i>Anorthic</i> , Haidinger, Miller, & Des Cloiszeaux. <i>Asymmetric</i> , Groth.	Three, of unequal length, all the intersections oblique.	None.	Anorthite. Albite. Cyanite.

The magnetic and electric properties of crystals, and their relations to heat, all shew the same intimate connection and dependence on their crystalline form observed in the case of their optic properties.

For fuller details of the subject treated of in this paper I would refer you to the many excellent text-books of mineralogy, and to the articles treating of the various divisions of the subject in the encyclopædias. A most excellent little work is that by Mr. Fletcher of the British Museum, from which I have freely quoted.

In conclusion I would call your attention to the fact that we Canadians have in our own country a vast unexplored field of research in crystallography. Canada has afforded the most magnificent crystals of many mineral species, which the world has ever seen. I need only mention the superb and unrivaled crystals of zircon, apatite, phlogopite, sphene &c. which grace the museums of Europe and this continent.

Many of our localities present unusually favorable conditions for studying the mode of formation of the various crystallized minerals, and if my remarks this evening awaken in some of my hearers an interest in the fascinating study of the wonderful laws governing structure in inorganic nature, my object will be accomplished.